PSR Report 706

Land-to-Seafloor Electromagnetic Transmissions in the 0.1 to 10 Hz Band

E. C. Field

March 31, 1977

PACIFIC·SIERRA RESEARCH CORP.
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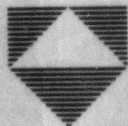

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During the summer of 1976, an electromagnetic propagation experiment was performed on the Olympic Peninsula in northwest Washington. The experimental goals were (1) to probe the suboceanic lithosphere by sending signals from land to the seafloor via the so-called down-under-up mode, and (2) to transmit ultra-low-frequency signals to deep receivers via the usual over-down mode.

A grounded horizontal electric dipole transmitter, with a peak moment of 1.6×10^5 A-m, was used to generate square-wave signals having periods from

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10 sec to 1 sec. Strong signals were received on a 100-m-long electrode pair emplaced on the seafloor at a depth of about 1000 ft and at a range of 22 km from the transmitter. The fundamental was received with a 20- to 30-dB signal-to-noise ratio (SNR), and many harmonics--14 in one case--were also clearly detected.

Calculations based on the assumption that the above-ground near-fields penetrate downward through the ocean to the receiver give results that agree well with the measurements at 22 km and 1000 ft; *viz.*, theory and experiment agree to within a factor of two for all periods transmitted and harmonics detected. Even if a relatively strong signal had reached the ocean through the suboceanic crust, it would have been masked by this over-down mode.

Measurements were also made on the seafloor at ranges from 110 to 135 km and a depth of 8000 ft, using receiving antennas 540 m to 1000 m in length. At these sites, the ocean screened out the over-down mode, and any signal detected would have had to propagate through the crust. Although the equipment was working well, no signals were detected.

Calculations based on the assumed existence of a uniform lithospheric waveguide of conductivity, σ_ℓ, show that a field would have been detected at 135 km and 8000 ft if $\sigma_\ell < 3 \times 10^{-3}$ mho/m. Thus, the *effective* conductivity of the propagation path must have been greater than 3×10^{-3} mho/m. However, the possible existence of a subduction zone on the propagation path raises doubts about the validity of interpreting the results in terms of effective conductivity.

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PREFACE

During the summer of 1976, scientists from Pacific-Sierra Research Corporation, the University of Texas, and Scripps Institute of Oceanography performed an electromagnetic propagation experiment on the Olympic Peninsula in the northwest corner of the state of Washington. The main purpose of the experiment was to send ultra-low-frequency signals from land to deep receivers on the seafloor. In addition, a number of subsidiary land-based measurements were carried out. This report describes and interprets the land-to-seafloor portion of the experiment.

SUMMARY

During the summer of 1976, an electromagnetic propagation experiment was performed on the Olympic Peninsula in northwest Washington. The experimental goals were 1) to probe the suboceanic lithosphere by sending signals from land to the seafloor via the so-called down-under-up mode, and 2) to transmit ultra-low-frequency signals to deep receivers via the usual over-down mode.

A grounded horizontal electric dipole transmitter, with a peak moment of 1.6×10^5 A-m, was used to generate square-wave signals having periods from 10 sec to 1 sec. Strong signals were received on a 100-m-long electrode pair emplaced on the seafloor at a depth of about 1000 ft and at a range of 22 km from the transmitter. The fundamental was received with a 20- to 30-dB signal-to-noise ratio (SNR), and many harmonics--14 in one case--were also clearly detected.

Calculations based on the assumption that the above-ground near-fields penetrate downward through the ocean to the receiver give results that agree well with the measurements at 22 km and 1000 ft; viz., theory and experiment agree to within a factor of two for all periods transmitted and harmonics detected. Even if a relatively strong signal had reached the ocean through the suboceanic crust, it would have been masked by this over-down mode.

Measurements were also made on the seafloor at ranges from 110 to 135 km and a depth of 8000 ft, using receiving antennas 540 m to 1000 m in length. At these sites, the ocean screened out the over-down mode, and any signal detected would have had to propagate through the crust.

Although the equipment was working well, no signals were detected.

Calculations based on the assumed existence of a uniform lithospheric waveguide of conductivity, σ_ℓ, show that a field would have been detected at 135 km and 8000 ft if $\sigma_\ell < 3 \times 10^{-3}$ mho/m. Thus, the *effective* conductivity of the propagation path must have been greater than 3×10^{-3} mho/m. However, the possible existence of a subduction zone on the propagation path raises doubts about the validity of interpreting the results in terms of effective conductivity.

ACKNOWLEDGMENTS

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I. INTRODUCTION

During the summer of 1976, a team made up of scientists from Pacific-Sierra Research Corporation, the University of Texas, and Scripps Institute of Oceanography undertook an electromagnetic propagation experiment on the Olympic Peninsula, in the northwest corner of the state of Washington. The main purpose of the experiment was to probe the suboceanic lithosphere by sending signals from land to the seafloor via the so-called down-under-up mode. In addition, ultra-low-frequency signals were sent to a very deep receiver via the usual over-down mode. Besides these sea-based measurements, a number of land-based measurements were carried out for other purposes. This report presents results and interpretation of the land-to-seafloor portion of the experiment.

Section II reviews the motivation for and concept of the experiment; Sec. III describes the experimental site, equipment, measurement procedures, and problems encountered; Sec. IV gives the experimental results; Sec. V presents a theoretical interpretation of the results; and Sec. VI gives the conclusions and discussion.

II. BASIS FOR THE EXPERIMENT

The existence of an electromagnetic lithospheric waveguide was first postulated more than twenty years ago (*Wait, 1954*). This waveguide's conformation is generally hypothesized as a layer of dry, resistive rock in the earth's crust. Bounded above by wet (hence, conductive) sedimentary crustal material and below by hot (conductive) mantle layers, the zone of resistive rocks would act as a propagation channel for electromagnetic signals.

A great deal of controversy has been generated by the waveguide hypothesis. Although many scientists agree that some sort of waveguide structure exists, widely varying estimates of its effective conductivity have caused considerable disagreement about its utility. Depending on methodology, geophysical area, and interpretation, estimates of minimum crustal conductivity have ranged from 10^{-9} mho/m to 10^{-2} mho/m. The former raises inferences of a lithospheric waveguide of great use for long-range communications, and the latter conductivity would rule out useful communications. The reader interested in examination and discussion of these previous estimates of crustal conductivity is referred to AGU Monograph 14 (*Heacock, 1971*), Crustal Studies Workshop Report (*Hales, 1972*), and reports by Field and Dore (*1973*), and Sternberg (*1975*). This report, however, is concerned solely with the summer 1976 land-to-seafloor propagation experiment.

A highly idealized illustration of the waveguide hypothesis is given in the schematic diagram in Fig. 1. Of course, the "boundaries" between the various crustal layers are not nearly so well defined as

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Ocean $\sigma = 4$

Sediment $\sigma = 1$

Moist Overburden

$\sigma = 10^{-2}$ to 10^{-4} mho/m

5 to 10 km

Dry Resistive "Waveguide" $\sigma = 10^{-2}$ to 10^{-9}
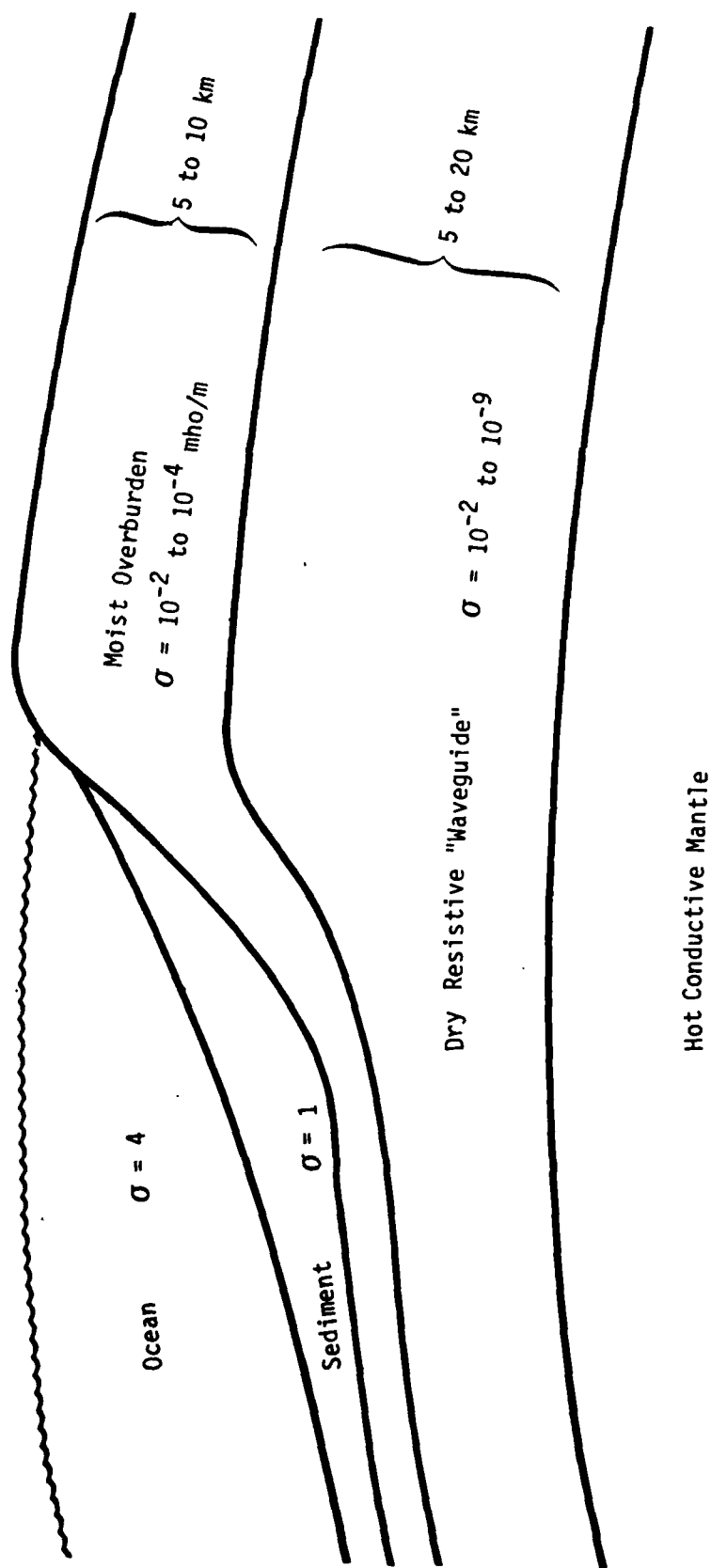
5 to 20 km

Hot Conductive Mantle

Fig. 1--Schematic of waveguide hypothesis

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those in the diagram; moreover, at interfaces between tectonic plates, waveguide discontinuities--not shown in Fig. 1--caused by subduction would be expected. We attempted to design the experiment to avoid such discontinuities. Nonetheless, the detailed structure of the lithosphere is not well known, and unsuspected discontinuities could affect the experimental results.

The conductivity of seawater is well known, and the conductivity of the seafloor sediments is believed known within a reasonable degree of accuracy. The 10^{-2}-to-10^{-4} mho/m range shown in Fig. 1 for the conductivity of the continental overburden is indicative of geographic variations rather than inherent uncertainties, and, at a given location, the effective conductivity of the overburden can, in fact, be measured fairly closely. The 10^{-2}-to-10^{-9} mho/m range for the conductivity of the postulated waveguide represents both variations between different geographic locations and inherent uncertainties. Even at a given location, conventional surface-based measuring techniques can, at best, establish a rough upper limit of the effective waveguide conductivity (*Heacock, 1971*), leaving the actual value uncertain by many orders of magnitude. The thicknesses of the various layers are also uncertain, as Fig. 1 shows, but this uncertainty is not nearly so critical to the potential utility of a crustal waveguide as is the uncertainty in lithospheric conductivity.

Because of the above factors, it was desirable to design an experiment to determine the effective propagation characteristics (i.e., the effective conductivity) of the crust, averaged over considerable distances. Single-point, surface-based techniques, such as magneto-

telluric or galvanic probing, are hampered because any field capable of "seeing through" the relatively highly conductive overburden is relatively insensitive to a deeper, highly resistive layer. Deep drilling to obtain rock samples from the desired depth is very expensive, particularly if a number of locations are to be sampled. Moreover, serious doubts exist as to whether removing a sample from its environment causes its electrical conductivity to change drastically from its *in situ* value.

The most convincing approach would, of course, be direct propagation between terminals emplaced in deep boreholes—expensive, even if only a single pathlength (i.e., two boreholes) were used. The fact that measurement of signal strength versus distance would require moving the receiver, and drilling several boreholes, makes the cost of this option even more of an inhibiting factor.

These considerations led to the experimental configuration shown schematically in Fig. 2. A grounded horizontal-electric-dipole (HED) antenna will excite several different modes. In addition to diffusing directly through the overburden, these modes can propagate in three distinct channels: the well-established earth-ionosphere waveguide, and postulated waveguides in the lithosphere and in the F-layer of the ionosphere. The properties of these modes (all of which have received widespread attention in the literature) are summarized by Field and Farquhar (*1975*), and are briefly discussed in subsequent sections of this report.

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~ 50 km

F-layer Waveguide Mode

Ionosphere

RCVR

XMTR

Air Mode

Ocean

Sediment

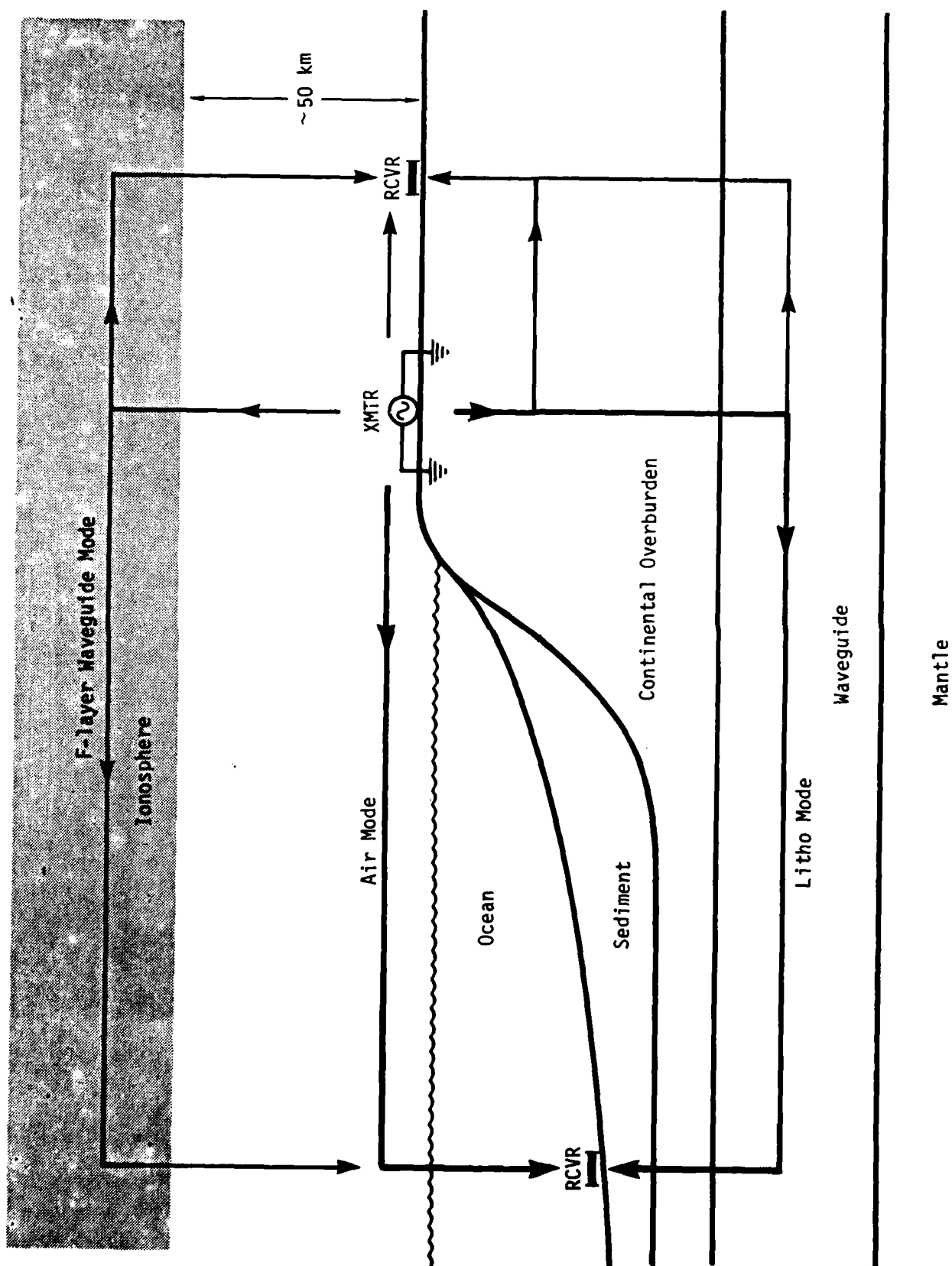Continental Overburden

Litho Mode

Waveguide

Mantle

RCVR

Fig. 2--Schematic diagram of the experiment

Interpretation of ground-to-ground measurements is complicated, because a means must be developed for untangling the contributions of the various modes. However, as shown by Field and Farquhar (*1975*) and as discussed in Secs. III through V below, the water depth and transmission range may be chosen such that the highly opaque seawater screens out the air mode and F-layer waveguide mode. Also, provided the lithospheric waveguide conductivity is low enough, it is possible to receive (solely) the litho mode with a receiver on the seafloor. Thus, the experiment is based on the fact that, if a favorable propagation channel exists in the lithosphere, the litho mode will suffer less attenuation over distances of hundreds of kilometers than does the air mode in 5,000 to 10,000 ft of seawater. Of course, for short ranges and shallow depths, the air mode can be received.

In summary, the experiment diagrammed in Fig. 2 has several desirable features:

1. At great enough ranges and depths, any signal received must consist solely of the postulated litho mode.

2. By retrieving and re-deploying the receiver, several pathlengths can be inexpensively monitored.

3. By using a sufficiently low frequency to penetrate the continental overburden, the need for a transmitter borehole is alleviated.

4. Atmospheric noise is greatly attenuated at great depths.

The experimental parameters selected to best take advantage of these features are given in the following section. Note that the price paid

for the attributes of the above configuration is that land-to-seafloor

propagation paths are not necessarily indicative of conditions between

two land-based, buried terminals. Thus, care must be exercised in

inferring general waveguide utility from the specialized conditions

that could exist near a shoreline.

III.   DESCRIPTION OF THE SUMMER-1976 EXPERIMENT

SITE SELECTION

Although subject to unavoidable uncertainties regarding geological structure, *a priori* information indicated that the coastal region selected was the best available in the continental United States for the following reasons:

- Seafloor-sediment thickness varies from about 2 km near shore to perhaps 0.1 km near the Juan de Fuca Ridge. Analysis shows that such sediments, as well as the continental overburden, could be penetrated by using wave frequencies below a few Hertz.

- Water depths of at least several thousand feet are needed to screen out the air mode and the F-layer waveguide mode, unwanted for the part of the experiment designed to probe the lithosphere. At the same time, the depth must be less than about 10,000 ft to facilitate emplacement and retrieval of the receiving package. Finally, transmission ranges of between 100 km and several hundred kilometers were found by Field and Farquhar (*1975*) to be optimum for probing the postulated waveguide. Figure 3 shows that the selected region satisfies all of these geometric constraints.
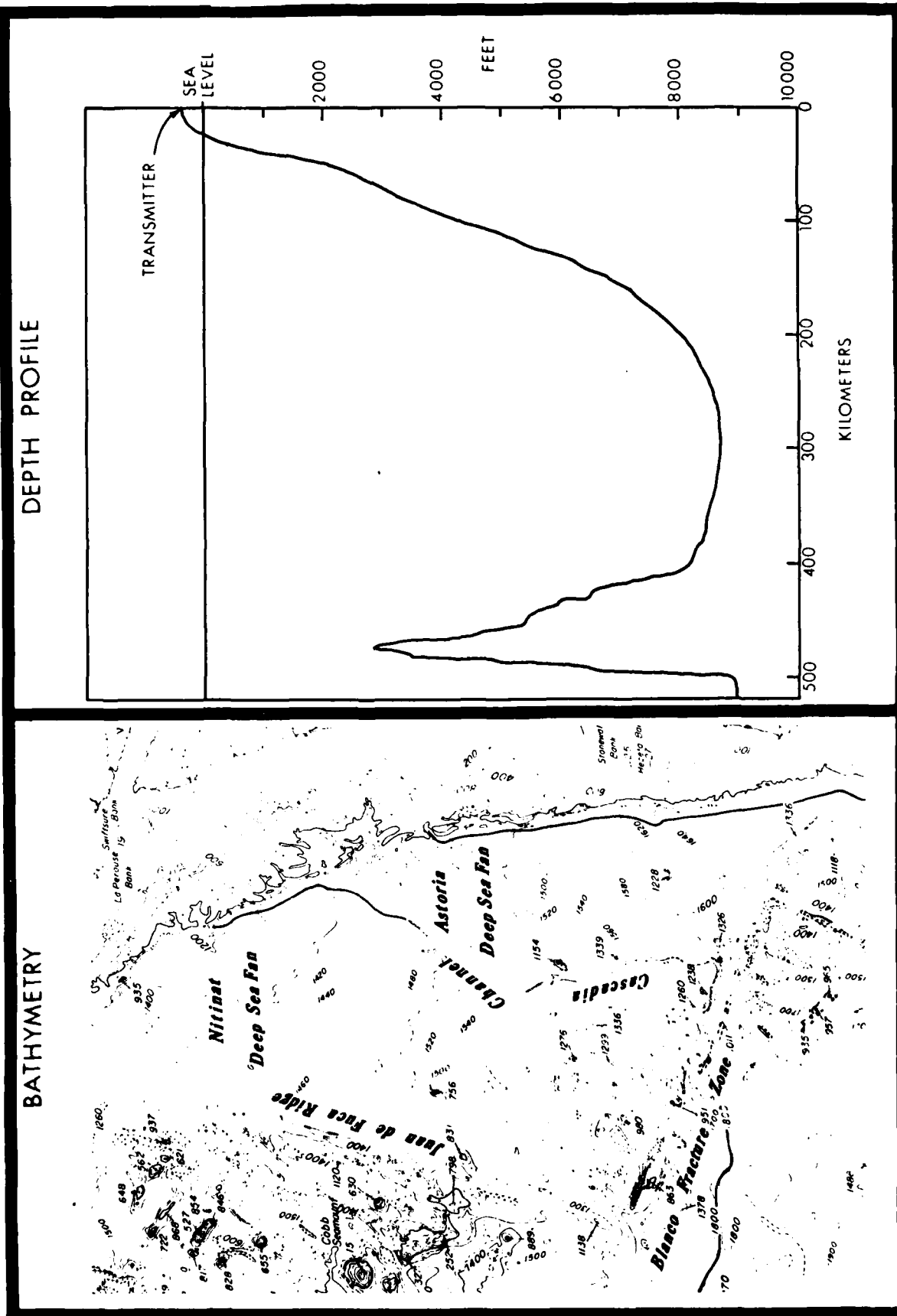
DEPTH PROFILE

BATHYMETRY

Fig. 3--Receiver site characteristics

• Judging from seismic records, the selected region

(Fig. 3) can be considered tectonically inactive.

Despite the favorable properties described above, we must acknowledge the significant uncertainties in the geological history of the area. According to Kulm and Fowler (*1963*), evidence from the Oregon Coast supports the possible existence of a subduction zone. The presence of such a subduction zone on a propagation path used in the experiment would adversely affect the chances for a positive result. A negative result caused by a subduction zone would not be indicative of propagation between two buried terminals on the continental United States.

TRANSMITTER

The transmitter used was a large, transportable, DC ground-tester leased from the Bonneville Power Administration. Alternating current was generated simply by electronically switching the current on and off at the desired frequency. Thus, the resultant current waveform was a raised square wave. The peak current capacity of the ground-tester is 200 A, and the minimum possible square-wave period about 0.05 sec; i.e., the frequency of the fundamental could be as high as 20 Hz. Of course, since square waves consist of an infinite series of odd harmonics, frequencies higher than 20 Hz would be contained in the higher harmonics. In the actual experiment, the shortest period used was 1 sec, and the peak current maintained at essentially 100 A throughout.

The transmitting antenna consisted of a one-mile-long wire buried about six inches below the surface and grounded at each end. The grounds were made by burying culvert pipes, and the combined resistance of both grounds was about 10 ohm. Thus, the peak transmitter electric dipole moment was about 100 A x 1609 m $\approx$ 1.6 x 10^5 A-m, and the peak power was about 10Ω x $(100A)^2 \approx$ 100 kW.

The transmitting antenna was emplaced about a mile from the shore, and was aligned at an azimuth of 60° so that the endfire direction was roughly perpendicular to the local shoreline. The antenna's approximate position is denoted by the X in Fig. 4.

SEAFLOOR RECEIVER

The seafloor receiver, developed and operated by Scripps, consisted of an AC voltmeter whose leads made contact with the sea through silver-silver chloride electrodes spaced at an interval, ℓ, and azimuth given in Table 1; i.e., the receiving antenna was a grounded horizontal electric dipole of length ℓ. This antenna lay on the seafloor and was thus capable of sensing a single component of the electric field parallel to the ocean bottom. The receiver/recorder package also lay on the seafloor, with no electrical connection to the surface. Figure 5 shows a schematic diagram of the electrodes, antenna, and recording system, and gives values for certain electrical parameters.

The seafloor antenna/receiver/recorder system was subject to various types of noise, some environmental. Figure 6 shows amplifier noise and recorder-system gain. Other noise sources included electrode noise, signals induced by moving water, and noise from sources above the surface, propagating through the ocean or through the underlying rocks.

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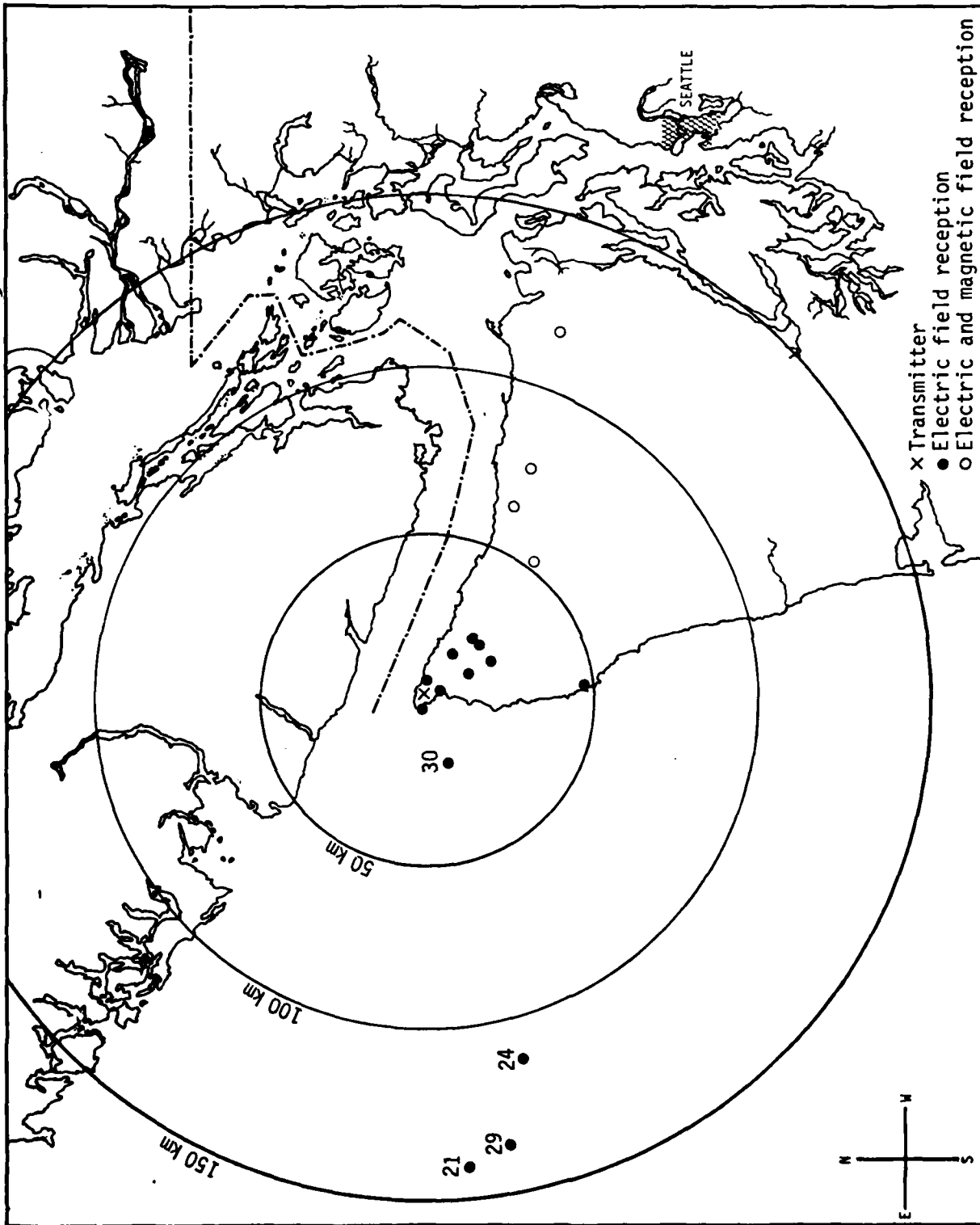
Fig. 4--Transmitter and receiver locations
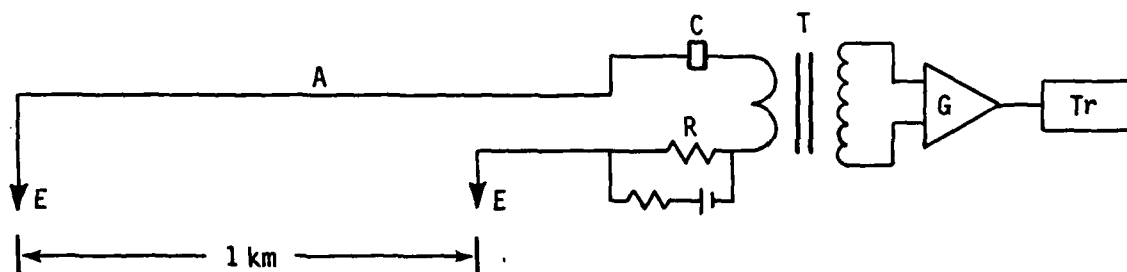
Fig. 5--Schematic diagram showing electrodes, antenna,
and recording system for seafloor emplacement

A   Insulated antenna (½ ohm)

B   Ag-AgCl electrodes (17-ohm typical)

C   0.1-Faraday electrolytic capacitor to
     isolate electrodes and transformer
     from DC currents

R   0.3-ohm resistor to provide 10-mv
     bias to C

T   Transformer, 1:120 turns ratio

G   AC amplifier

Tr   Voltage-controlled oscillator and
     FM tape recorder
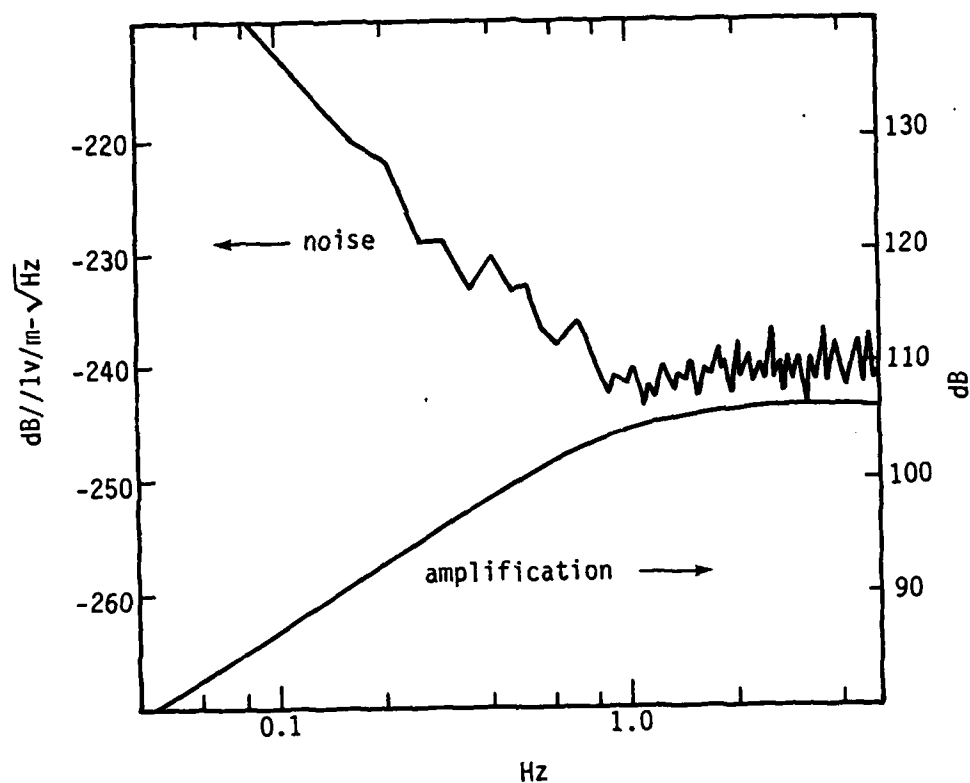
Fig. 6--Amplification of recorder system and
noise level for passive resistive
source. Noise is referred to 1-km
antenna. These figures are applicable
to measurements on 21 August. On 24
and 29 August, the antenna was some-
what shortened, and on 30 August
the preamplifier was desensitized
by a factor of 0.27 and the antenna
was shortened to 100 m.

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The receiving gear was deployed and retrieved from the M/V *Wild Goose*, a yard minesweeper converted and used as a luxury yacht in recent years. The *Wild Goose* was modified for the experiment over a period of five days. Considerable special equipment—a winch, a STANCO/HAP-2 crane, a storage spool, a davit, floats, etc.—was installed, and a computer van for on-board processing was secured on the forward portion. Deployment required at least several hours, and involved slowly playing out the seafloor apparatus on many thousands of feet of nylon line while moving at a very slow rate of advance. Following emplacement, the line was attached to a marker buoy and set adrift. The boat's engines were shut down during transmission, and the package was recovered after transmission. The recorder batteries provided 84 min of power before they needed recharging. The sequence of emplacement, recording, and retrieval required about 1-1/2 days at the deep-water sites, because the entire sequence could not be carried out within a single daylight period, and nighttime deployment/retrieval was considered too dangerous.

LAND-BASED RECEIVERS

In addition to the seafloor measurements that are the subject of this report, a number of land-based measurements were made by the University of Texas. Because these measurements provide a useful calibration of the transmitter and give insight into the properties of the transmitter site, we briefly set forth the ground-based receiver characteristics. Horizontal electrical field measurements were made on crossed, buried electrode pairs with nominal electrode spacing of

500 ft. Magnetic field measurements were made on crossed, vertical-
plane coils sensitive to the horizontal magnetic field. These receivers
were used to measure amplitude, phase, and azimuth of the horizontal
components of electric and magnetic fields.

MEASUREMENTS

Table 1 summarizes the sea-based measurements and denotes certain
problems encountered. For example, the primary antenna and recorder
were lost on 17 August, and the remaining measurements were made with
the backup rig. Note from Table 1 that the length of this backup
antenna became somewhat shorter, due to damage and repairs, as the
measurement program progressed.

On four days—21, 24, 29, 30 August—valid measurements were
made in the sense that the receiver was deployed and retrieved and
transmissions were made. However, the measurement of 24 August is
considered less reliable than the others, because the antenna fouled
badly on the recorder package and the quality of the data is poor.
The approximate locations of these measurements, labeled with the
appropriate dates, are shown in Fig. 4. The transmission log for
these dates is shown in Table 2. The peak transmitter current in
all cases was 100 A.

Several breaks in the transmission are evident from Table 2.
These breaks occurred because, for safety reasons, we shut the trans-
mitter down when livestock wandered close to an electrode. These
brief transmission breaks do not noticeably affect the results, because
signal phase was preserved on restarting the transmission, thus
permitting integration of the entire signal.

Table 1

SUMMARY OF OBSERVATIONS AT SEA--AUGUST 1976

Date	Recorder start time PDT	Recorder position LORAN ILO	ILI	Lat(N) Long (W)	Depth (m)	Azimuth of antenna from recorder (± 20°)	Length of antenna (m)
17	0230	Antenna and recorder lost during recovery attempt				---	---
21	1936	4054	2258	48°15.1'N 126°38.0'W	2500	085°	1000
24	1830	4046	2381	48°04.6'N 126°29.5'W	2551	060°	700
27	1600	Tape recorder failed		---	---	---	---
29	0600	4046	2354	48°07.0'N 126°33.0'W	2405	080°	540
30	1200	4280	2714	48°17.3'N 124°59.5'W	312	050°	100

Table 2

TRANSMISSION LOG FOR SEAFLOOR MEASUREMENTS

Date	Local Time of Transmission	Square-Wave Period
8/21	1930-2027	1 sec
	2030-2032	1 sec
	2037-2100	1 sec
8/24	1824-1844	10 sec
	1857-1921	10 sec
	1924-2000	10 sec
8/29	0559-0642	10 sec
	0642-0730	5 sec
8/30	1158-1228	10 sec
	1229-1255	3 sec
	1256-1329	1 sec

Although ground-to-ground transmissions are not discussed in detail in this report, we have, for completeness, indicated in Fig. 4, the locations of the active land-based measurements. In addition, a number of passive magnetotelluric soundings were made to assess the electrical properties of the transmitter region.

IV. EXPERIMENTAL RESULTS

The data obtained on 21, 24, 29, and 30 August, 1976, were subjected to two types of processing: calculation of an auto-correlation function to determine whether a detection had been made; and calculation of a power spectrum.

We begin by presenting the 30 August results, the only ones showing detections of the transmitted signals. The range and receiver depth on 30 August were 22 km and 1023 ft, respectively. Figure 7 shows the normalized power spectrum and auto-correlation function calculated from 130 sec of data taken during transmission at a 1-sec period. The auto-correlation function demonstrates almost perfect periodicity, indicating a very strong detection. This positive result is confirmed by the power spectrum, which shows three strong and extremely narrow spikes at the fundamental and third and fifth harmonics. Additional harmonics are evident when the power spectrum is plotted on a more easily inter-preted, linear frequency scale. The narrowness of the spectral spikes indicates extremely stable transmission and propagation. The fundamental shows a signal-to-noise ratio (SNR) of more than 20 dB.

Figure 8 shows power spectrums calculated from data taken during transmissions at periods of 3 sec (390-sec sample) and 10 sec (1300-sec sample). The results are even more striking than those for a 1-sec period. A SNR of nearly 30 dB is exhibited by each fundamental. For the 10-sec period, 14 harmonics--the first through the twenty-seventh-- are clearly identifiable.

The power spectrums of Figs. 7 and 8 are given in dimensionless units. The electric field strengths corresponding to the spectral
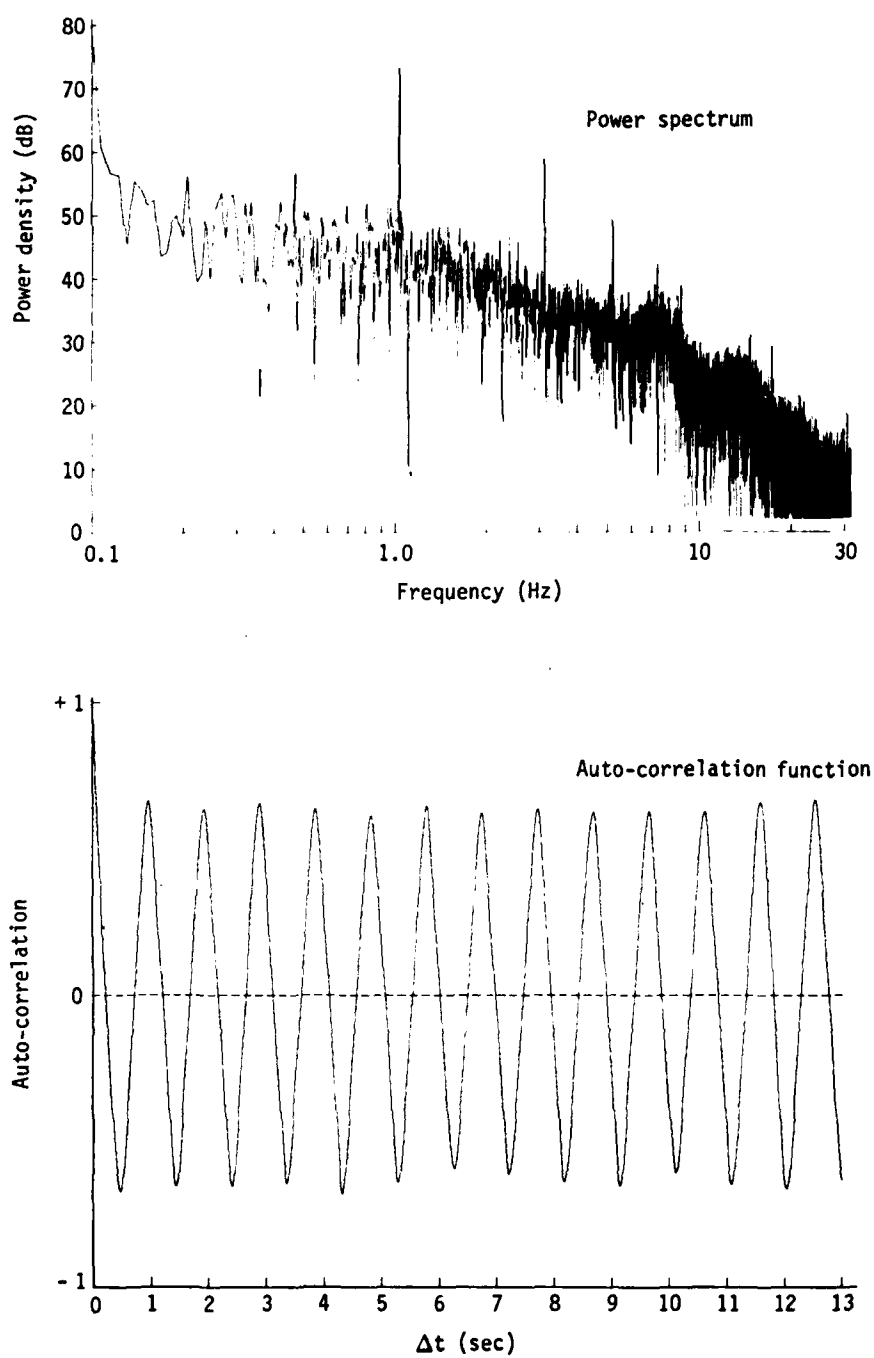
21

Fig. 7--Normalized power spectrum and auto-correlation function;
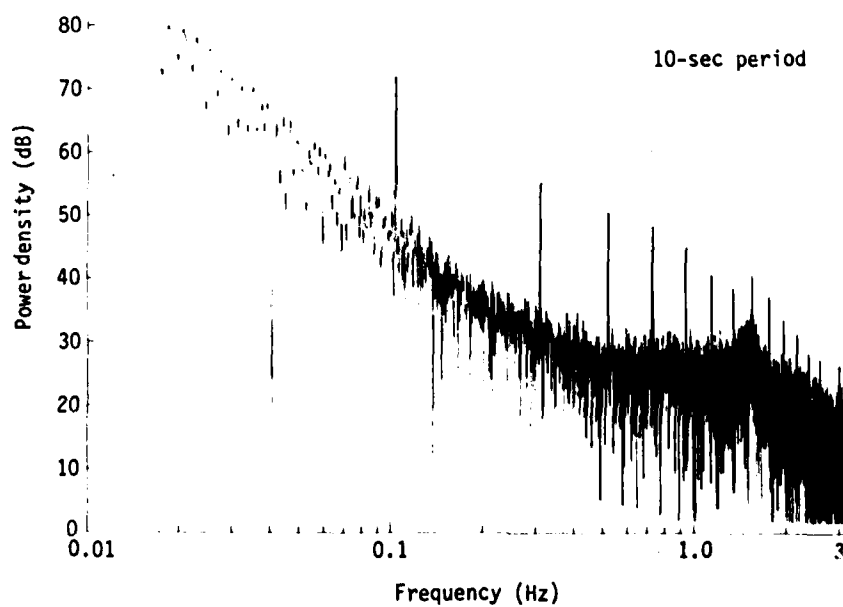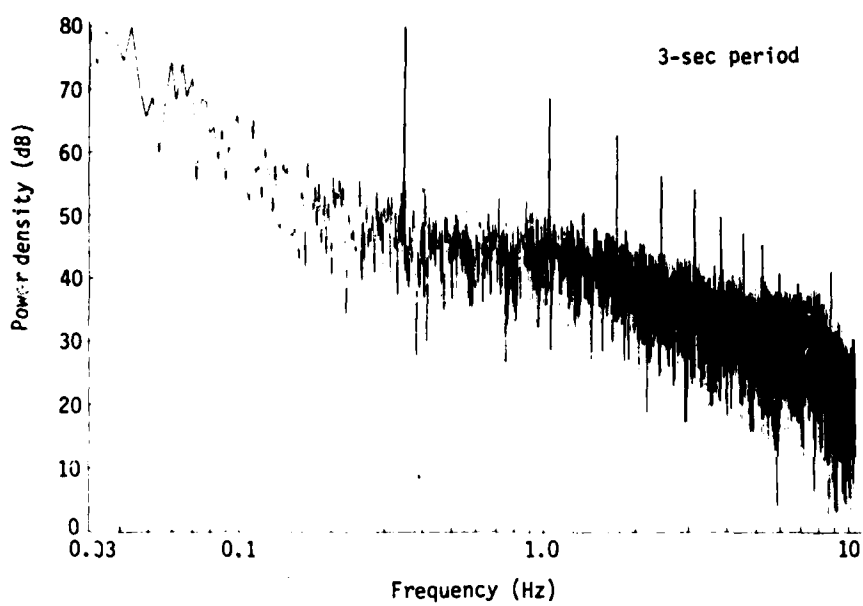30 August, 22-km range, 1023-ft depth, 1-sec period

Fig. 8--Power spectrums; 30 August, 22-km range, 1023-ft depth

peaks in these spectrums have been calculated, taking into account all receiver characteristics, such as antenna length. These measured harmonic field strengths are shown in Figs. 9 through 11 (X's). The calculated values plotted in Figs. 9 through 11 are discussed in Sec. V.

Power spectrums and auto-correlation functions were also calculated for the longer range, deep-water data acquired on 21, 24, and 29 August. Careful inspection indicated no perceptible periodicity in the auto-correlation function and no spectral peaks in the power spectrums.

The fundamental spectral peaks with a 100-m antenna in 1000 ft of water (Figs. 7 and 8) exhibit SNR of 20 to 30 dB. Background noise at the 8000-ft depths of the 21, 24, and 29 August measurements was less intense than at the 1000-ft depth of the 30 August measurement, and the antenna on 21, 24, and 29 August was a factor of 5 to 10 longer than on 30 August (see Table 1, p. 18). We thus infer from the absence of a signal on 21, 24, and 29 August that the seafloor fields were at least 40 to 50 dB smaller than shown in Figs. 9 through 11.
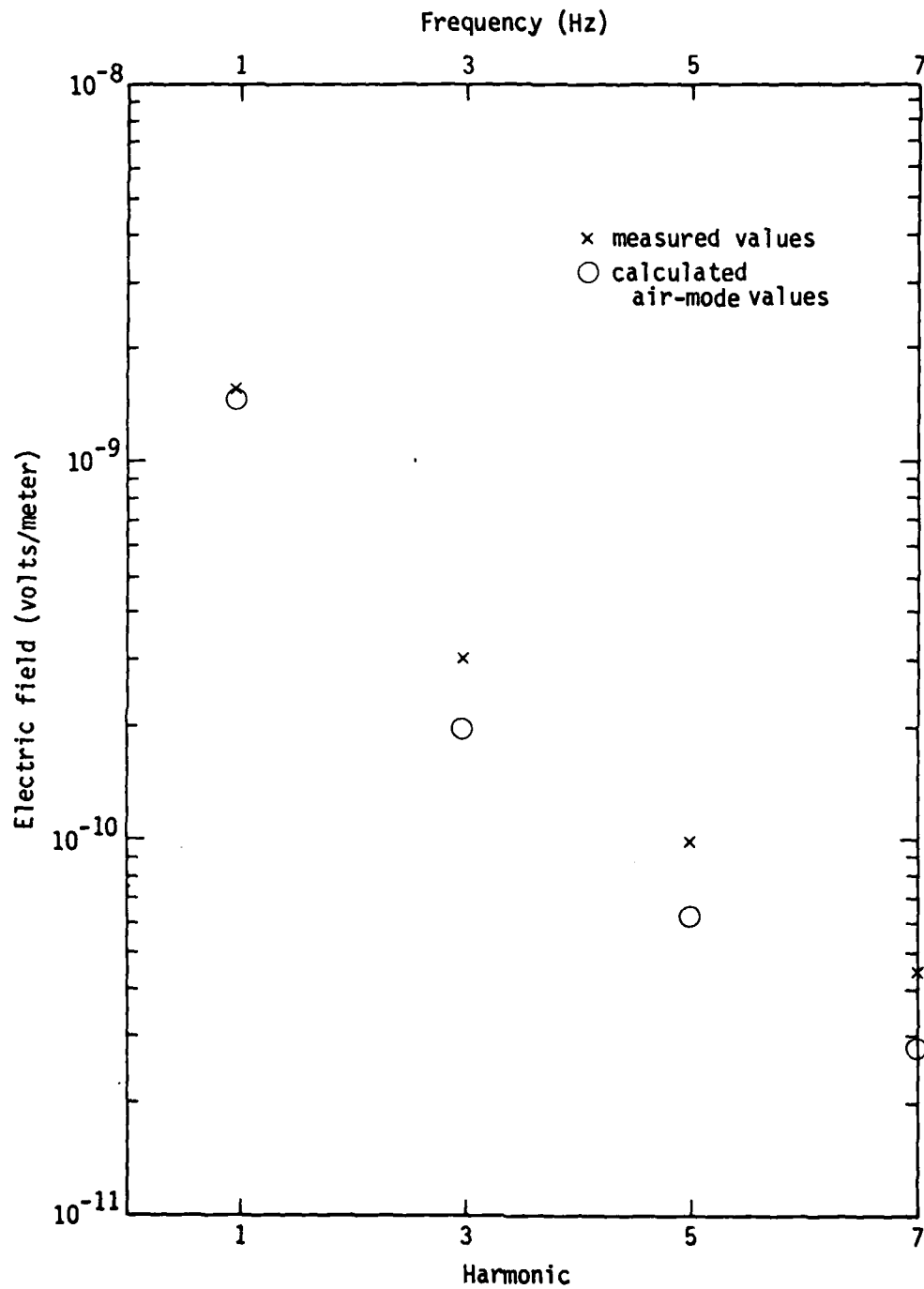
Fig. 9--Calculated and measured seafloor fields; 30 August, 1-sec period.
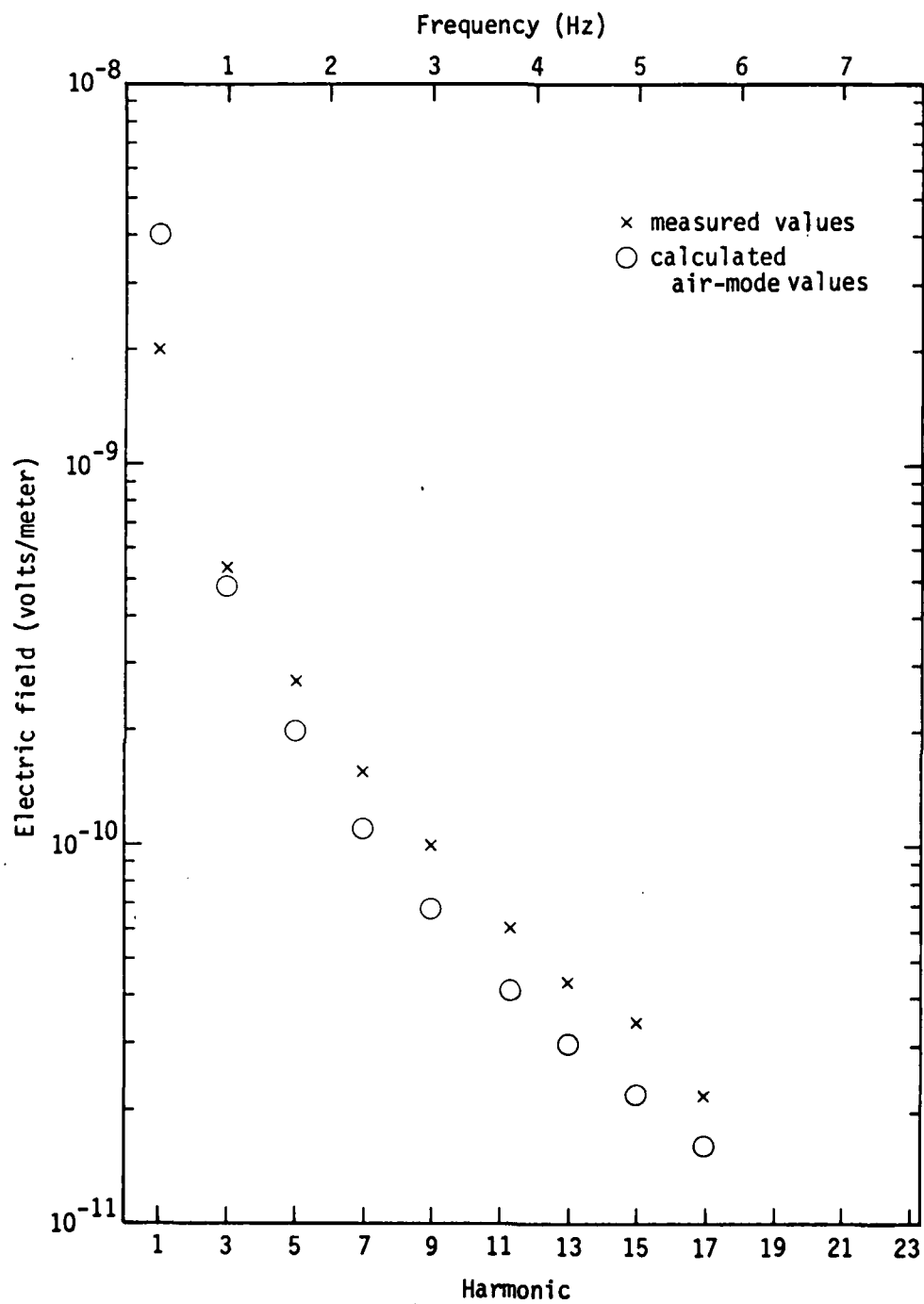
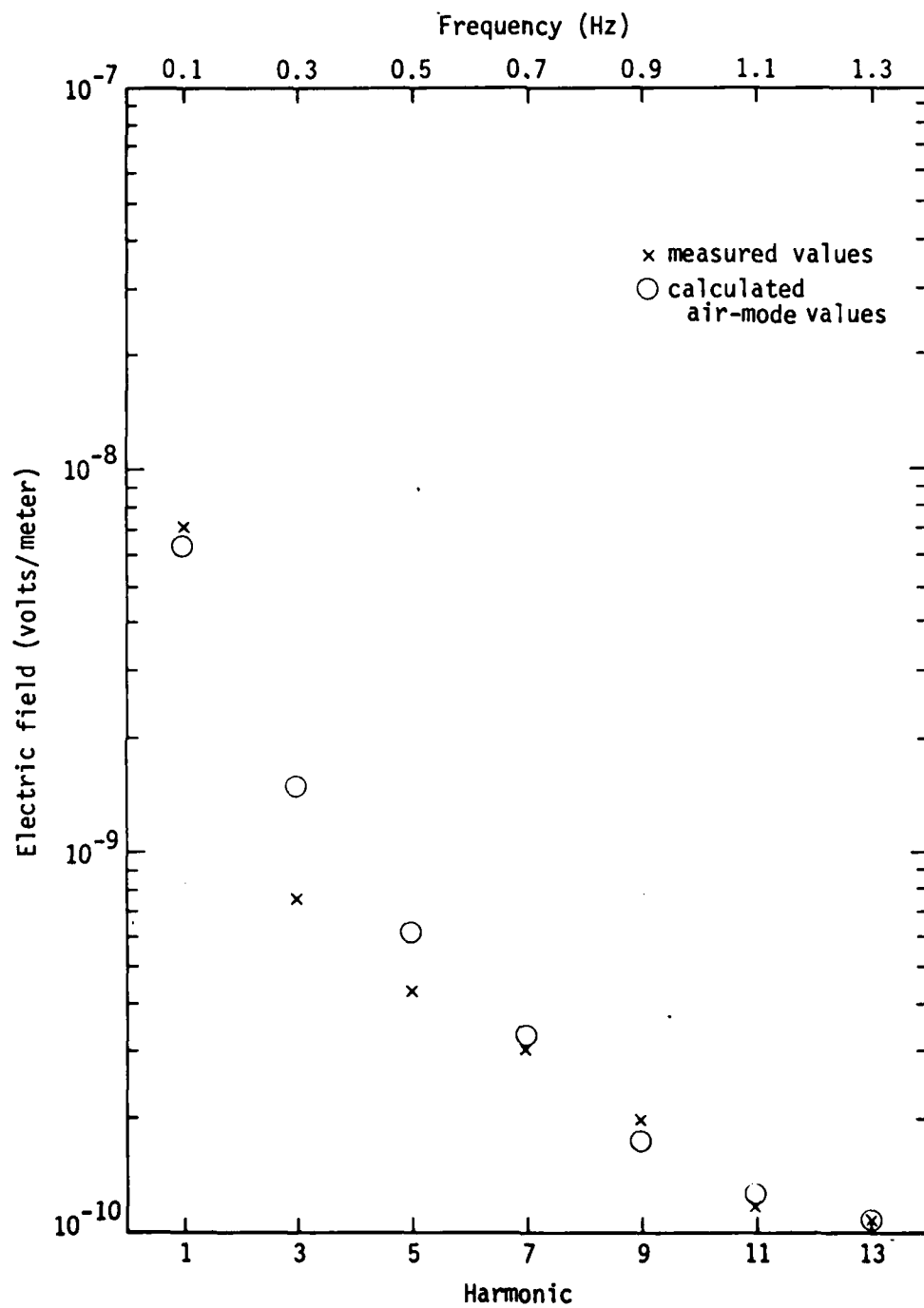Fig. 10--Calculated and measured seafloor fields; 30 August, 3-sec period

Fig. 11--Calculated and measured seafloor fields; 30 August, 10-sec period

V. INTERPRETATION OF DATA

DATA FROM 30 AUGUST

Our first aim here is to show that electric fields calculated from equations describing the air mode agree closely with the measured fields shown in Figs. 9 through 11. Because the free-space wavelengths of 0.1-to-10-Hz signals are tens of megameters or more, near-field equations must always be used to describe the air mode. The spatial dependence of the near-field is contingent on whether the lateral transmission range, r, is greater or smaller than the ionospheric reflection height, h. If r < h, the fields are well approximated by Kraichman's (1970) expression for an electric dipole over a conducting half-space, an expression which predicts a $1/r^3$ dependence. For r > h, the fields become nearly two dimensional, and Greifinger and Greifinger's (1974) expressions, which predict a $1/r^2$ dependence, should be used.

A composite near-field expression that behaves properly when r/h is small or large is

$$E \simeq \frac{\tilde{I}L}{2\pi\sqrt{\sigma_s\sigma_o}} \left(\frac{h+r}{hr^3}\right) e^{-d/\delta} \qquad \text{v/m} \qquad , \qquad (1)$$

where E is the electric field; $\tilde{I}$ is the peak transmitting antenna current; L is the transmitting antenna length (1609 m); σ_s is the conductivity of seawater (4 mho/m); σ_o is the effective conductivity of the earth at the transmitter; d is the receiver depth; and δ is the skin depth of the wave in seawater. Equation (1) applies for a sinusoidal current. We used

a raised square wave for the current waveform; therefore, I(t) is given by

$$I(t) = I/2 + \frac{2I}{\pi} \sum_{N=1,3,\ldots} \frac{\sin 2\pi Nt/T}{N} \quad . \quad (2)$$

where T is the square-wave period. Thus, $\tilde{I} = 2I/\pi$, where 1 is the peak square-wave current (100 A).

By inserting $\tilde{I}$ into Eq. (1), it follows that the strength, E_N, of the Nth harmonic of the seafloor field is given by

$$E_N = \frac{IL}{N\pi^2} \frac{e^{-d/\delta}}{\sqrt{\sigma_s \sigma_o}} \left(\frac{h + r}{hr^3}\right) \qquad v/m \quad . \quad (3)$$

Strictly speaking, Eqs. (1) and (3) should contain angular factors representing antenna azimuth and bearing. However, to within the $\pm 20°$ uncertainty that the receiving-antenna azimuth is known (Table 1, p. 18), it is justifiable to neglect these angular factors and assume perfectly aligned transmitting and receiving antennas.

All parameters in Eq. (3) are accurately known except the ionospheric height, h, and the ground conductivity, σ_o. The height, h, can reasonably be assumed to be 50 km and, in any event, only modestly affects the results if $r < h$, which is the case for the 30 August measurements.

The effective ground conductivity, σ_o, at the transmitter can be estimated from either active or passive land-based measurements made during the experiment. An equation analogous to Eq. (3), but with $d = 0$,

describes the ground-level magnetic field. The magnetic field is insensitive to the electrical properties of the ground at the receiver, and this equation for the magnetic field thus depends only on σ_o. Calculations not included here show that using $\sigma_o \approx 8\times10^{-3}$ mho/m at 0.1 Hz, $\sigma_o \approx 10^{-2}$ mho/m at 0.33 Hz, and $\sigma_o \approx 2.5\times10^{-2}$ mho/m above 1 Hz gives excellent agreement between calculations and the land-based magnetic field measurements. Moreover, these values are compatible with the results of passive magnetotelluric soundings. We note in passing that σ_o decreases with decreasing frequencies, indicating a conductivity that decreases with increasing depths.

The above estimates for σ_o are, of course, quite rough. Fortunately, σ_o enters Eq. (3) as a square root, and even a factor-of-four error in σ_o would cause only a factor-of-two error in the calculated value of E_N. Using the above values for σ_o and h in Eq. (3) gives the calculated values shown in Figs. 9 through 11. The agreement between experiment and theory is closer than a factor of two for *all three square-wave periods and all harmonics.* This agreement—which is excellent, considering the approximations made and uncertainties in geophysical parameters—leaves little doubt that the air mode made a major contribution to the seafloor signals detected on 30 August.

The above conclusion does not imply that a crustal signal did not reach the receiver, but, rather, that a simple calculation of the air mode seems to adequately explain the data; i.e., no crustal signal is needed to reconcile experiment and theory. Because of the great strength of the air mode, a crustal signal 20 dB above noise—but still weaker than the air mode—could have been received but gone undetected.

An estimate of the signal that could have reached the receiver via a suboceanic path requires consideration of the specific structure of the propagation path. Figure 12, which is based on information provided by Cox,[*] illustrates (not to scale) the best available model of the suboceanic crust at the site of the experiment. As mentioned above, there is some evidence that a subduction zone could conceivably exist in the region. Such a zone is not shown in Fig. 12.

As indicated in Fig. 12, the 30 August measurement was made in a trench, the motivation being to achieve the greatest receiver depth compatible with a short transmission path. Although convenient for experimentation, this geometry is not amenable to analytic calculation of the crustal signal. The main reason for this computational difficulty is that the pathlength is of the same order of magnitude as the thickness of crustal layers, thus invalidating the usual approximations based on the assumption of layer thicknesses much smaller than the transmission pathlength. The necessary numerical calculation is beyond the scope of this report. Of course, this difficulty with identifying and interpretating the crustal signals for short paths and water depths less than several thousands of feet is the reason that most detection attempts were made in 8000 ft of water at ranges greater than 100 km.

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[*]C. Cox, Scripps Institute of Oceanography, private communication, 1977.
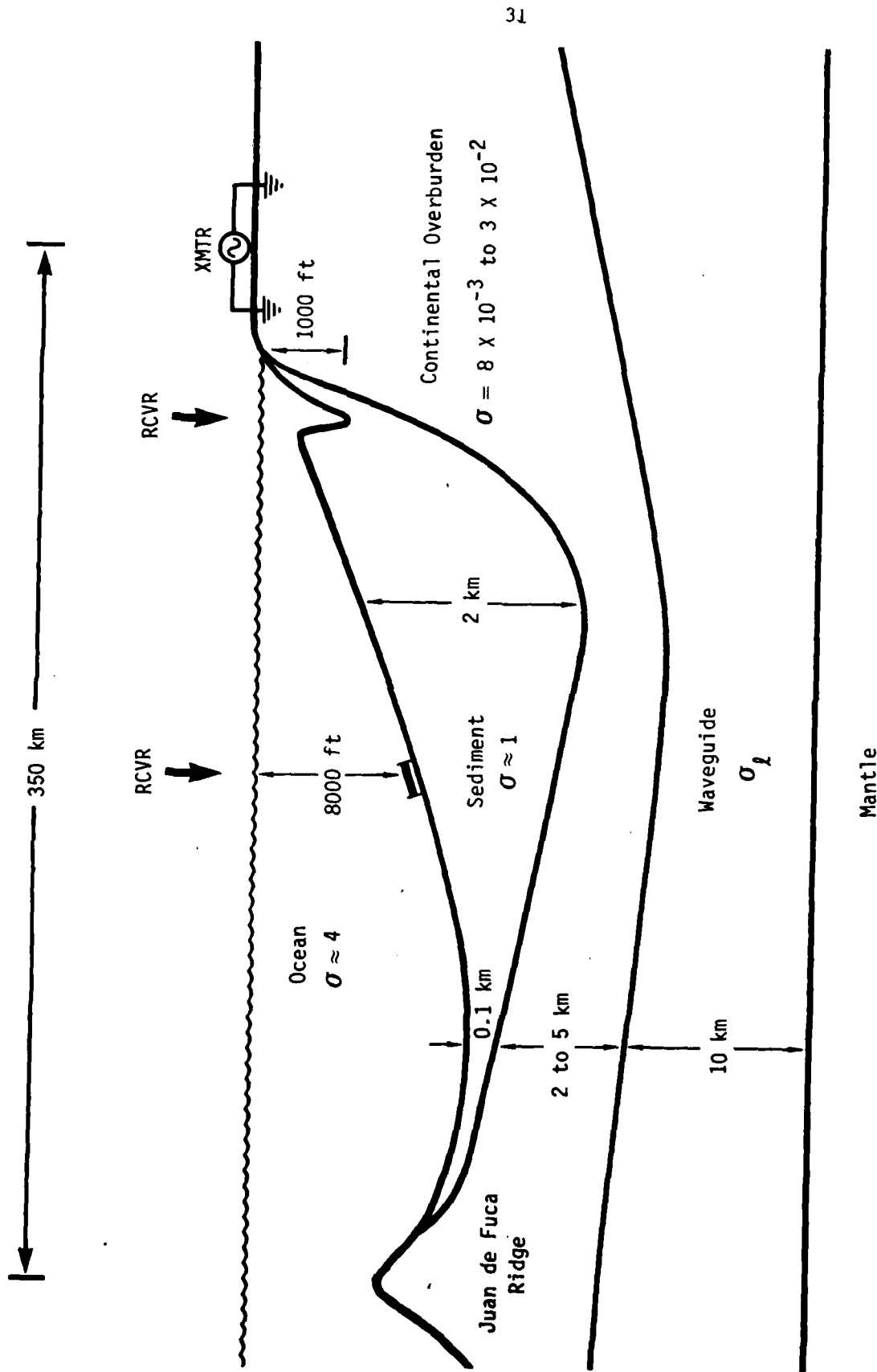
Fig. 12--Schematic diagram of site and geometry of land-to-seafloor transmission experiment

The following labels appear in the figure:

- 350 km
- XMTR
- 1000 ft
- Continental Overburden
- $\sigma = 8 \times 10^{-3}$ to 3×10^{-2}
- RCVR
- 2 km
- Waveguide
- σ_ℓ
- Mantle
- RCVR
- 8000 ft
- Sediment
- $\sigma \approx 1$
- Ocean
- $\sigma \approx 4$
- 0.1 km
- 2 to 5 km
- 10 km
- Juan de Fuca Ridge

DATA FROM 21, 24, 29 AUGUST

The measurements on 21 and 29 August, considered more reliable than the 24 August measurement, were made at about 135-km range and 8000-ft water depth. Insertion of these parameters into Eq. (3) shows that even the air-mode harmonic at 0.1 Hz—the strongest one—had a strength of only 5×10^{-12} v/m at the receiver. This field was thus below the detection threshold at 0.1 Hz, which is shown below to be roughly 2×10^{-11} v/m. Higher air-mode frequencies/harmonics were much further below the corresponding thresholds. Thus, in accordance with the experimental design, the air mode was undetectable at the 135-km/8000-ft sites, and any signal detected would have had to have penetrated the suboceanic crust.

The non-detection of signals on 21 and 29 August shows that the fields at the seafloor must have been below the frequency-dependent detection threshold. Since a field would have been detected if the effective conductivity of the waveguide were low enough, we can use the non-detection to set a lower limit on this effective conductivity.

Effective conductivity is defined as the conductivity that a *uniform* lithospheric waveguide must possess to give the same signal transfer function as the actual crust. We emphasize that a lower limit on *effective* conductivity is related to a lower limit on *actual* conductivity only for stratified structures such as those shown in Fig. 12. Non-uniformities (e.g., subduction zones, which diminish the transmitted signals) would cause the lower limit on effective conductivity to be much larger than that on the actual conductivity.

With the above caveat in mind, we proceed to use the model shown in Fig. 12 to estimate the lower limit on effective waveguide conductivity for the experimental propagation paths. The proper equation to use for the electric field depends on whether the receiver is within the near-field or far-field of the transmitter.

The following near-field expression (*Field and Farquhar, 1975*) applies if the skin depth, δ_ℓ, in the waveguide exceeds the transmission range:

$$E_N \approx \frac{IL}{N\pi^2} \frac{e^{-d_o/\delta_o} \, e^{-d_s/\delta_s} \, e^{-r/\delta_\ell}}{\sqrt{\sigma_s \sigma_o} \; r^2 H} \qquad \text{v/m} \qquad (4)$$

In Eq. (4), d_o is the *total* path (down *and* up) traversed in the over-burden; δ_o is the skin depth in the overburden; d_s is the sediment thick-ness at the receiver; δ_s is the skin depth in the sediment; and H is the thickness of the postulated lithospheric waveguide. The analogy between Eqs. (4) and (3) which describes near-fields in the earth-ionosphere waveguide, is evident.

When $\delta_\ell <$ r, the following far-field expression describes the contribution of the lithospheric waveguide mode to the signal at the seafloor:

$$E_N = \frac{2}{\pi N} \frac{\sigma_\ell IL}{\sqrt{\sigma_o \sigma_s}} \left(\frac{\omega \mu_o}{4H}\right) \left(\frac{2c}{\pi\omega}\right)^{1/2} \left(\frac{\omega E_o}{\sigma_\ell}\right)^{1/4} \frac{e^{-r/\delta_\ell} \, e^{-d_o/\delta_o} \, e^{-d_s/\delta_s}}{r^{1/2}} \quad \text{v/m} \quad , \quad (5)$$

where ω is the angular frequency of the Nth harmonic; c is the vacuum speed of light; and E_o and μ_o are the electric and magnetic permittivity.

of free space, and σ_ℓ is the effective waveguide conductivity. Recall that $\sigma_\ell^{1/2}$ also is contained implicitly in the skin depth, δ_ℓ.

The detailed derivation of Eq. (5) is somewhat tedious and is given by Field and Farquhar (*1975*); however, the physical significance of the terms is evident by inspection. All terms except the last two exponentials (e^{-d_o/δ_o} and e^{-d_s/δ_s}) correspond simply to propagation between horizontal dipoles in a plane waveguide. The difference between these terms and the usual equation for ELF propagation in the earth-ionosphere waveguide (e.g., *Bannister, 1974*) is caused by the fact that conduction currents are dominant in the lithosphere, whereas displacement currents are, of course, dominant in free space. The last two terms clearly account for absorption suffered in propagating down to the waveguide and then up again to the receiver.

Equations (4) and (5) are used in their respective regimes of validity to obtain the graphs of electric field strength versus σ_ℓ shown in Figs. 13 and 14. The parameters used correspond to the 29 August measurement; *viz.*, r = 135 km and T = 10 sec and 5 sec.[*] Other parameters used were H = 10 km, d_o = 5 km, σ_s = 4 mho/m, and σ_o = 8.3 x 10^{-3} mho/m. As shown in Fig. 12, the sediment thickness at the 29 August receiver site is believed to be about a kilometer. However, to assess the sensitivity of the results to uncertainties in sediment thickness, graphs are also given (Figs. 13, 14) for the pessimistic assumption that d_s = 2 km. In all cases, the sediment
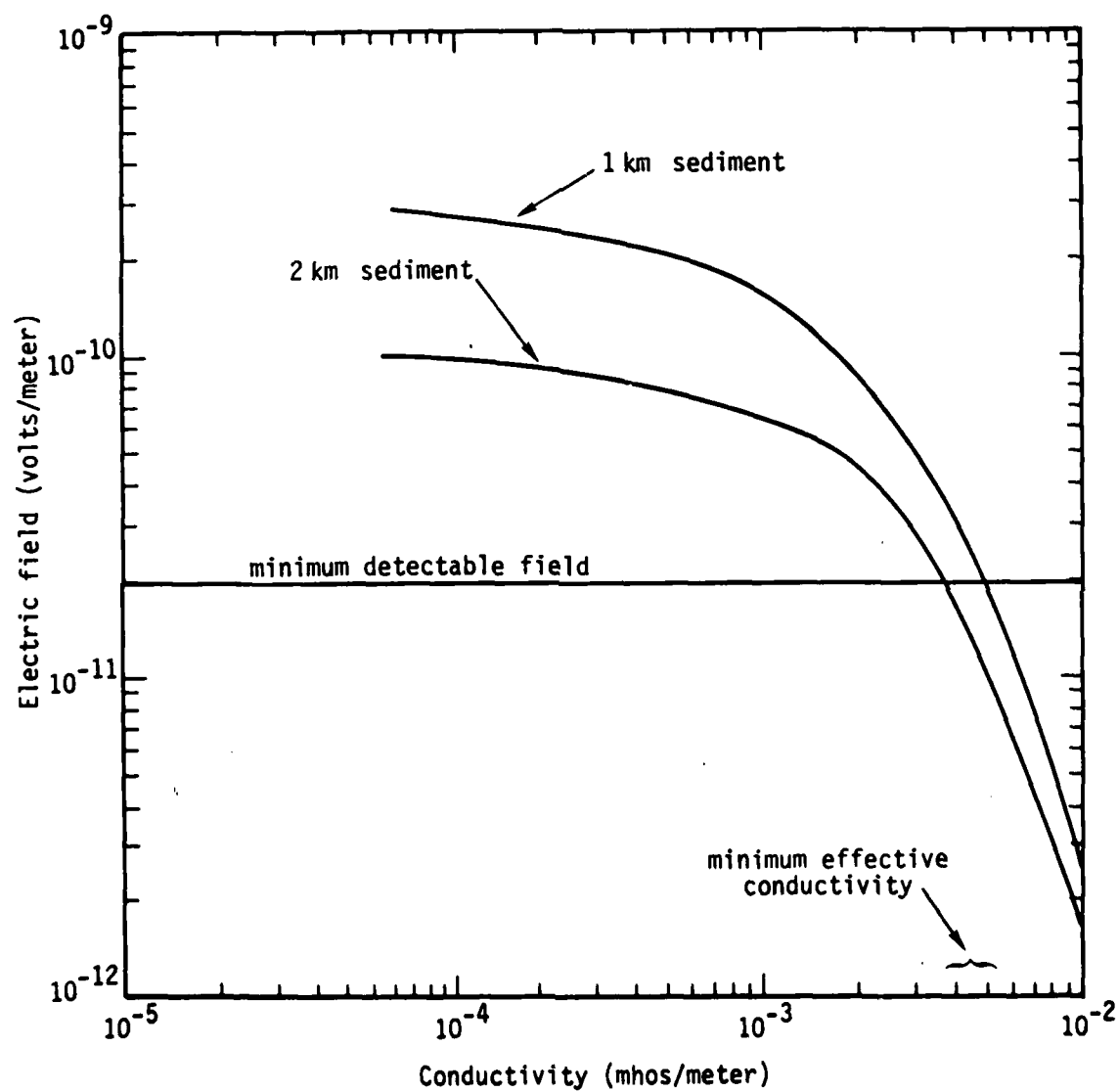
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[*]$\omega = 2\pi/T$ in Eq. (5).

Fig. 13--Seafloor field strength versus effective waveguide
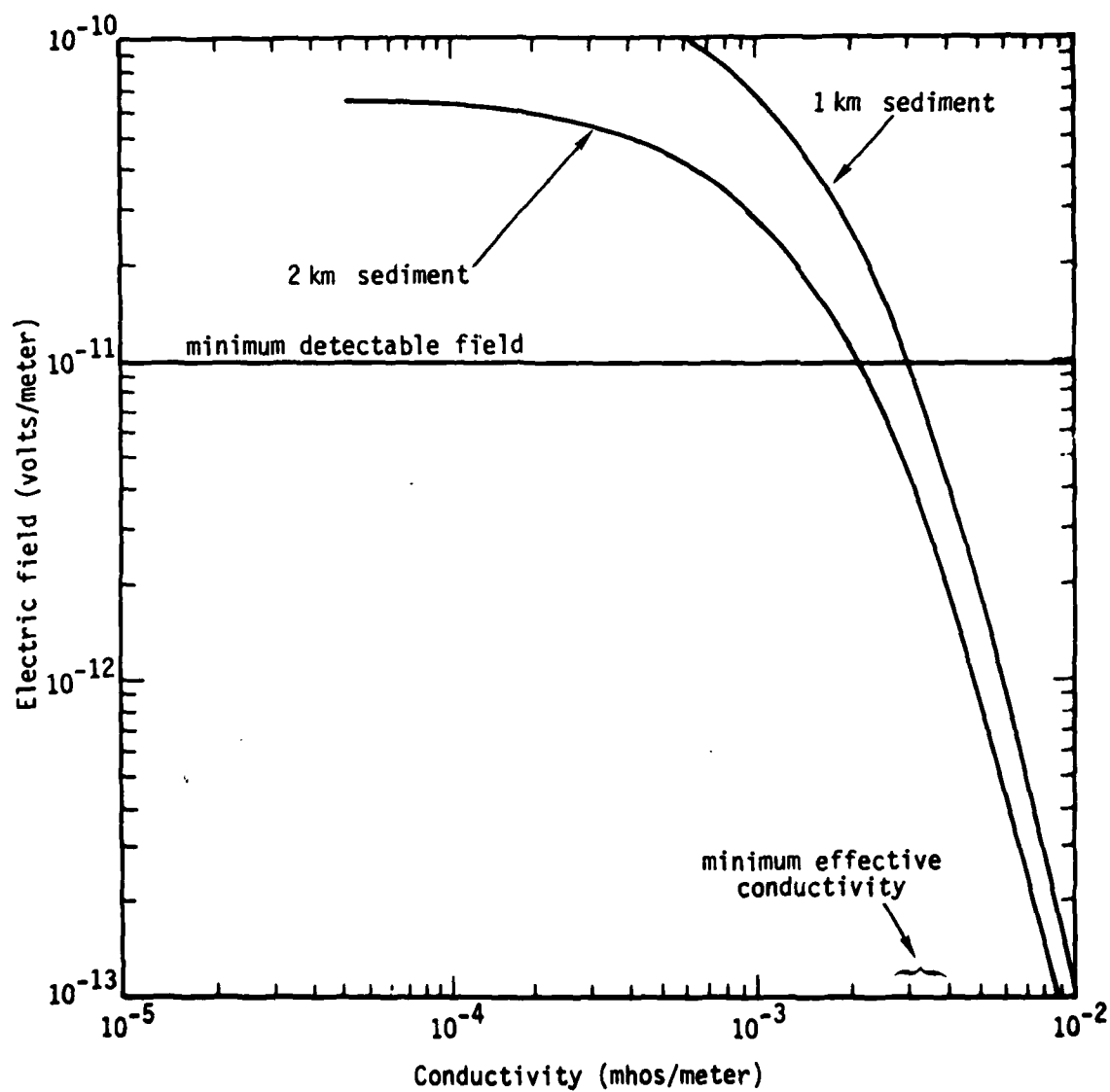conductivity; T = 10 sec, range = 135 km

Fig. 14--Seafloor field strength versus effective waveguide
conductivity; T = 5 sec, range = 135 km

conductivity was assumed equal to 1 mho/m.

It might be argued that uncertainties in overburden thickness could render the calculated fields unreliable. But because the overburden skin depth exceeds the sediment skin depth by about an order of magnitude, a 10-km uncertainty in overburden thickness, d_o, would affect the electric field about as much as only a 1-km uncertainty in sediment thickness, d_s. Since it is unlikely that a 10-km uncertainty in d_o exists, we believe that the $d_s = 2$ km curves in Figs. 13 and 14 adequately illustrate the lower limit on the signal.

The minimum detectable fields (i.e., the detection thresholds) are shown in Figs. 13 and 14. These thresholds, 2×10^{-11} v/m and 10^{-11} v/m, are lower than the 6×10^{-10} v/m (at 0.1 Hz) and 2×10^{-10} v/m (at 0.3 Hz) judged from Figs. 7 through 11 to have been the thresholds on 30 August. The 29 August thresholds are lower because

1. A 2400-sec integration time was used in processing the 29 August data.

2. The antenna was 540-m long on 29 August, compared with 100 m on 30 August.

3. Atmospheric noise is much more heavily attenuated at an 8000-ft depth than at a 1000-ft depth.

4. Water currents and, hence, flow-induced noise, are smaller at 8000 ft than at 1000 ft.

The results of Figs. 13 and 14 show that, if the effective conductivity were smaller than about 3×10^{-3} mho/m, the fields would have exceeded the threshold and would have been detected. Since no detections were made, the results indicate an effective conductivity larger than

3×10^{-3} mho/m. Note that this conclusion is the same for both square-wave periods considered, and is remarkably insensitive to sediment thickness--and, hence, overburden thickness.

The above estimate of effective conductivity is, of course, approximate, and uncertainties do exist. Nonetheless, the low conductivities--10^{-5} mho/m or less--necessary for long-range crustal communications, clearly did not exist unobstructed over the experimental propagation paths.

VI. CONCLUSIONS AND DISCUSSION

A grounded horizontal electric dipole transmitter, with a peak moment of 1.6×10^5 A-m, was used to generate square-wave signals having periods from 10 sec to 1 sec. Strong signals were received on a 100-m-long electrode pair emplaced on the seafloor at a depth of about 1000 ft and at a range of 22 km from the transmitter. In all cases, the fundamental was received with a 20- to 30-dB signal-to-noise ratio (SNR), and many harmonics--14 in one case--were also clearly detected.

Calculations based on the assumption that the above-ground near-fields penetrate downward through the ocean to the receiver give results that agree well with the measurements at 22 km and 1000 ft. Specifically, theory and experiment agree to within a factor of two for all periods transmitted and harmonics detected. We thus conclude that the above-ground near-field--also known as the air mode or over-down mode--made a major contribution to these measured fields. Even if a relatively strong signal had reached the receiver through the suboceanic crust, it would.have been· swamped by this air mode and, hence, would have been undetectable.

The strong detections at 22-km range and 1000-ft depth demonstrate the feasibility of using ultra-low-frequency signals to communicate to deeply submerged receivers over short ranges. Somewhat longer ranges or greater depths could have been achieved, because the SNR at the measurement site was much larger than that required for detection.

Measurements were also made on the seafloor ranges at 110 to 135 km 'and a depth of 8000 ft, using receiving antennas 540 m to 1000 m in length. At these sites, the ocean screened out the air mode, and any signal

detected would have to propagate through the crust. Although the
equipment was working well, no signals were detected.

Calculations based on the assumed existence of a uniform lithosphere
waveguide of conductivity, σ_ℓ, show that a field would have been detected
at 135 km and 8000 ft if $\sigma_\ell < 3\times10^{-3}$ mho/m. Thus the effective conduc-
tivity of the propagation path must have been greater than 3×10^{-3} mho/m.
We emphasize that the minimum *effective* conductivity bears little resem-
blance to the minimum *actual* conductivity if the propagation path
contains non-uniformities or discontinuities. Thus, the possible
existence of a subduction zone on the propagation path raises doubts
about the validity of interpreting the results in terms of effective
conductivity.

REFERENCES

Bannister, P. R., "Far Field Extremely Low Frequency (ELF) Propagation Measurements, 1970-1972," *IEEE Trans. on Comm.*, Vol. COM-22, April 1974, p. 468.

Field, E. C., and M. Dore, *Electromagnetic Communications in the Earth's Crust*, Pacific-Sierra Research Corporation, PSR Report 306, June 1973.

Field, E. C., and J. A. Farquhar, *An Underwater Experiment to Assess Electromagnetic Communications in the Earth's Crust*, Pacific-Sierra Research Corporation, PSR Report 516, December 1975.

Greifinger, C., and P. Greifinger, *Feasibility of ULF Communication Via Earth-Ionosphere Waveguide*, R&D Associates, RDA-TR-4600-05, July 1974.

Hales, A. L., *A Multidisciplinary Program of Investigation of the Possibility of an Electromagnetic Waveguide in the Earth's Crust*, University of Texas at Dallas, 7 March 1972.

Heacock, J. G. (ed.), *The Structure and Physical Properties of the Earth's Crust*, AGU Monograph 14, 1971.

Kraichman, M. B., *Handbook of Electromagnetic Propagation in Conducting Media*, Naval Material Command, NAVMAT P-2302, 1970.

Kulm, L. D., and G. A. Fowler, "Oregon Margin Structure and Stratigraphy: A Test of the Imbricate Thrust Model," *Geology of Continental Margins*, C. A. Burk and C. L. Drake (eds.), Springer-Verlag, New York, 1964.

Sternberg, B., *Comparison of Measurements and Two-Dimensional Modeling of the Flambeau Anomaly, Wisconsin*, Department of Geology and Geophysics, University of Wisconsin, Madison, February 1975.

Wait, J. R., "An Anomalous Propagation of Radio Waves in Earth Strata," *Geophysics*, Vol. 19, No. 2, 1954.